Ecological Economics 147 (2018) 179–188

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Measuring Embodied Blue Water in American Diets: An EIO Supply Chain Approach☆,☆☆

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ARTICLE INFO

Keywords:
Blue water
Environmental input-output model
Food policy
Healthy diet
Sustainability
U.S. food system

ABSTRACT

Food systems worldwide rely on water resources that are facing demand from a growing population while regional water supplies are increasingly uncertain due to climate change. In this environment, dietary changes may have the potential to reduce water used in food production. At the same time, it is well established that American diets need to change in order to align with Federal healthy eating guidelines. In this article, we examine if there are synergies between healthier diets and blue water conservation in the U.S. food system. We estimate blue water use by supply chain stage using a multi-regional environmental input-output model. Then, we link this blue water to individual food items and use mathematical optimization to model healthy diet scenarios that meet the Dietary Guidelines for Americans. We find that while healthier U.S. diet outcomes and blue water conservation can be synergistic, these goals may also be competing. Making minimal changes from current American consumption to a healthy omnivore or vegetarian diet, blue water use increases by 16%, but the omnivore and vegetarian diets reduce embodied blue water by 63 and 66%, respectively, when the objective is to minimize water use.

1. Introduction

As obesity rates in the United States reach an all-time high at 39.8% (Hales et al., 2017) and costly, diet-related diseases continue to rise (USDA and HHS, 2015), the healthfulness of Americans has become an irrefutable national concern. Dietary choices not only impact health outcomes of individuals, but also the environment due to the resources used as inputs throughout the food supply chain. Freshwater is an important input in food production and, in fact, about 80% of the consumptive water use in the United States can be attributed to agriculture (USDA-ERS, 2013). Freshwater is a finite natural resource that is being depleted (Dalin et al., 2017) and that is facing increasing stress due to climate change and a growing global population (Distefano and Kelly, 2017; Vörösmarty et al., 2000). There is evidence that large-scale shifts in the types and quantities of foods consumed would affect water use throughout the food supply chain.

Combining multiple dimensions of diets, such as health and environmental impacts, has been coined as sustainable nutrition (Gustafson et al., 2016). The notion of sustainable nutrition has been around for decades (Gussow and Clancy, 1986) and there are a number of European studies on this topic, with greenhouse gas emissions (GHGE) the most commonly examined environmental impact (e.g., Baroni et al., 2007; Donati et al., 2016; Macdiarmid et al., 2012; Masset et al., 2014; Saxe et al., 2013; Scarborough et al., 2014; Tukker et al., 2011; Vieux et al., 2013; Wallén et al., 2004). This literature is mostly consistent; plant-based foods are more efficient than animal-based foods and healthy diets reduce environmental impacts compared to current dietary patterns.

Considering European diets and the water footprint of consumption, Vanham et al. (2013a) analyze the diets from four European zones. They find that their healthy and vegetarian diet scenarios reduce the blue water[1] footprint in all the zones, except the healthy diet in the north. Their results also find that a vegetarian diet has a lower water footprint than the reference and healthy diets in each respective zone. Vanham et al. (2013b) study the water footprint associated with the EU28 diet. They find that each of their three healthy diet scenarios reduce blue water compared to the reference diet, with the vegetarian diet resulting in the largest reduction of water. More recently, Vanham et al. (2016) study thirteen Mediterranean cities and analyze three healthy diet scenarios: an omnivore, a pesco-vegetarian, and vegetarian diet. They find that all three diet scenarios reduce the water footprint (blue and green components included) in all of the Mediterranean

☆ This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.
☆☆ Disclaimer: The views presented here are those of the authors and do not necessarily reflect official policy of ERS or USDA.
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[1] Blue water is surface and groundwater, green water is rainwater, and grey water is the freshwater required to absorb pollutants (Hoekstra and Mekonnen, 2012).

https://doi.org/10.1016/j.ecolecon.2017.12.028
Received 29 March 2017; Received in revised form 31 October 2017; Accepted 22 December 2017
Available online 03 February 2018
0921-8009/ Published by Elsevier B.V.

cities. The reductions range from 5% when switching to the healthy omnivore diet (Turkish Food-Based Dietary Guidelines) in Instanbul or Ankara to 53% when switching to a healthy vegetarian diet (Mediterranean diet pattern) in Jerusalem or Pisa.

However, there are only a few studies that consider both environmental and health impacts of U.S. dietary patterns. Environmental impacts considered in these U.S.-based studies include energy (Canning et al., 2017; Pimentel and Pimentel, 2003), carbon dioxide emissions (Rehkamp et al., 2017), GHGE (Eshel and Martin, 2006; Heller and Keoleian, 2015; Weber and Matthews, 2008), and land use (Peters et al., 2007; Peters et al., 2016).

Some papers expand the scope from one to multiple environmental impacts of U.S. diets and include water (Birney et al., 2017; Eshel et al., 2014; Gephart et al., 2016; Marlow et al., 2009; Tom et al., 2016). Studies by Birney et al. (2017), Gephart et al. (2016), and Tom et al. (2016) all rely on water footprint data from Mekonnen and Hoekstra (2010a, 2010b, 2011, 2012).

Most relevant to our work are the two papers (Birney et al., 2017; Tom et al., 2016) that consider the impact of changing dietary patterns on blue water use. Using the Dietary Guidelines for Americans, 2010 (DGA) as a benchmark for a healthy diet (USDA and HHS, 2010), Tom et al. (2016) evaluate three scenarios: the first reduces calories to the recommended levels, the second aligns the diet with the recommended food mix, and the third is consistent with both the calorie and food mix in the DGA. The authors find that blue water is reduced in Scenario 1 by 9% and blue water increases in Scenarios 2 and 3 by 16 and 10%, respectively. Birney et al. (2017) also consider a diet conforming to the 2010 DGA in both calories and food groups. The authors find that total blue water would increase from 162,000 to 186,000 l of water per capita annually, an increase of 15%.

We contribute to the sustainable nutrition literature by exploring whether there are synergies between healthier diets and blue water conservation in the U.S. food system. We use an environmental input-output (EIO) model to estimate the blue water used in the U.S. food system based on current American diets and a mathematical optimization model to generate four healthy diet scenarios. We compile the data for the multiregional environmental input-output (MEIO) model using an improved method of assigning annual blue water withdrawals[2] throughout the national economy. We build the data up from county-level allocations of water use by industry and final market users for more accurate national estimates that take into account regional heterogeneity. To our knowledge, this paper is the first assessment of water use embodied in American diets using the MEIO framework.

2. Methods

The input-output (IO) methodology that was first developed by Leontief (1941) and extended to consider environmental flows throughout the economy (Leontief, 1970). EIO models measure material flows of environmental consequence in physical units. EIO modeling is a type of life-cycle assessment because it allows for measurement of water use (and other materials), not only on the farm, but throughout the food supply chain.

In 2003, the United Nations, the European Commission, the International Monetary Fund, the Organisation for Economic Co-operation and Development, and the World Bank jointly issued a handbook that provides economic accounting guidelines for member nations and recommends the EIO approach as a best practice for achieving "a consistent analysis of the contribution of the environment to the economy and of the impact of the economy on the environment" (UN et al., 2003, p. iii). Additionally, the National Research Council (2002) identifies EIO analysis as an effective approach to model water use. Wiedmann (2009) presents a review of articles that have used this type of modeling to evaluate a range of environmental impacts, including water, in a single region or multiple regions. Other papers have been written using EIO models to evaluate water use in Australia (Lenzen and Foran, 2001), Spain (Cazcarro et al., 2013; Dietzenbacker and Valezquez, 2007; Duarte et al., 2002; Velazquez, 2006), China (Zhang and Diaz Anadon, 2014; Zhao et al., 2008), the United States (Blackhurst et al., 2010; Dang et al., 2014; Debaere and Kurzendoerfer, 2017; Mubako et al., 2013), and many countries (Lenzen et al., 2013). Others measure the resources embodied in diets in Europe (Tukker et al., 2011) and Australia (Hadjikakou, 2017; Reynolds et al., 2015) using EIO models.

Our preferred method of measuring embodied water is the EIO model because it is a top-down approach within a systems framework meaning we can characterize all of the economic and environmental transactions within the U.S. economy. This differs from another well-known approach of calculating water footprints.[3] Specifically, we employ a MEIO model, which extends conventional IO multiplier analysis to consider the physical flows for materials of environmental consequence in different geographical regions.

2.1. Multiregional Environmental Input-Output Model

Linking embodied water withdrawals to food-related final demand (GDP plus imports) begins with specification of the type I output multiplier model,[4]

$$\mathbf{x}^f = (\mathbf{I} - \mathbf{TA})^{-1}\cdot\mathbf{T}\cdot\mathbf{y}^f \leftrightarrow \mathbf{x}^f = \mathbf{L}\cdot\mathbf{T}\cdot\mathbf{y}^f \quad (1)$$

This multiregional multiplier model includes: (i) a final demand vector, $\mathbf{y}^f = [\mathbf{y}^{f1} \ldots \mathbf{y}^{fR}]'$, comprised of stacked regional C element final demand vectors for regions 1 to R—it summarizes total annual personal consumption expenditures (PCE) on food across C commodity groups; (ii) a gross industry-output vector, $\mathbf{x}^f = [\mathbf{x}^{f1} \ldots \mathbf{x}^{fR}]'$, comprised of stacked gross regional industry-output vectors; (iii) a direct requirement matrix, $\mathbf{A} = [\mathbf{A}^1 \ldots \mathbf{A}^R]''$, comprised of block diagonal regional direct-requirement matrices, and (iv) a rank CxR diagonal unit matrix, $\mathbf{I}$. We use the shorthand, $\mathbf{L} = (\mathbf{I} - \mathbf{TA})^{-1}$, to denote the total requirement matrix. In addition, there is a multiregional commodity-trade matrix comprised of bilateral commodity trade coefficient matrices among regions:

$$\mathbf{T} = \begin{bmatrix} \mathbf{T}_{11} & \ldots & \mathbf{T}_{1R} \\ \vdots & \ddots & \vdots \\ \mathbf{T}_{R1} & \ldots & \mathbf{T}_{RR} \end{bmatrix}$$

Each $\mathbf{T}_{sr}$, $\forall\, r,s \in R$, is a diagonal sub-matrix reporting the share of each commodity, $c \in C$, flowing from region s to r, such that each row of the full $\mathbf{T}$ matrix sums to 1 or 0 depending on whether the source region does or does not have gross output of the row commodity.

To extend this type I output multiplier model to an MEIO model, we introduce the environmental direct requirement matrix,

$$\mathbf{w}^f = \mathbf{E}\cdot\mathbf{L}\cdot\mathbf{T}\cdot\mathbf{y}^f = \mathbf{E}\cdot\mathbf{x}^f, \quad (2)$$

where $\mathbf{E}$ is the environmental direct requirement matrix of dimension $O \times (C \times R)$, and $\mathbf{w}^f$ (mnemonic for water in current context) is a O element column vector summarizing total environmental flows of each indicator, $o \in O$, embodied in total food PCE. For example, if $o = 1$ represents fresh surface water withdrawals, then $\mathbf{E}[o,(c \times r)]$ is the direct surface water withdrawal requirement per unit of industry c output in region r, and $\mathbf{w}^f[o]$ is total surface water withdrawals embodied in food PCE. For this study, we classify all blue water withdrawals into two categories: surface water and groundwater.

[2] We use "withdrawals" and "use" synonymously, as does the U.S. Geological Survey.

[3] For a comparison of these two methods see Daniels et al. (2011) and Feng et al. (2011).

[4] We represent matrices (vectors) using bold upper (lower) case letters, and sets or set elements using italicized alphanumeric. The symbol "′" denotes a transpose operation, "″" a diagonal matrix, and "$^{-1}$" a matrix inversion.

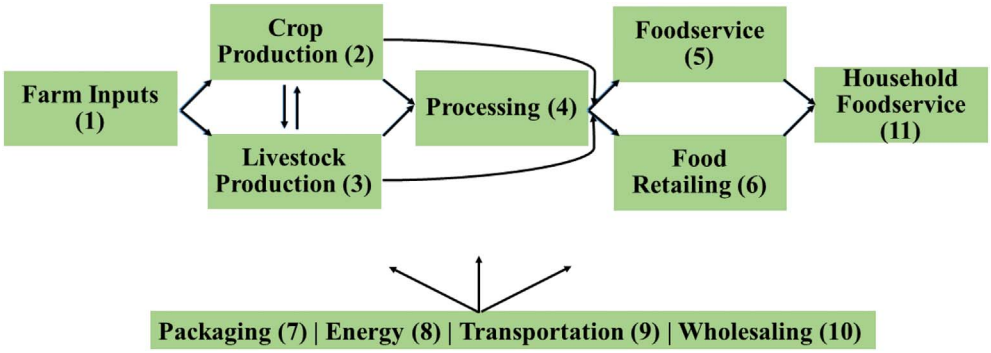

Fig. 1. Food supply chain stages.

Several assumptions, guided by our research application and data availability, greatly simplify calibration of MEIO parameters. First, if $\mathbf{A}^*$ is the national average direct requirement multiplier matrix, we assume $\mathbf{A}^* = \mathbf{A}^r \; \forall \; r \in R$. Next, if $dLn(\mathbf{y}^{f*})$ is the national average per capita percentage change in food expenditures linked to alterative diet outcomes in our analysis, we assume $dLn(\mathbf{y}^{f*}) = dLn(\mathbf{y}^{fr}) \; \forall \; r \in R$. Finally, we use the trade pool method (Leontief, 1953) of calibrating inter-regional trade coefficients:

$$\mathbf{T}_{s,r} = (\mathbf{A}^* \cdot \mathbf{x}^r + \mathbf{y}^r)'' \cdot ((\mathbf{x}^{\#})'')^{-1} \; \forall \; s, r \in R, \tag{3}$$

where $\mathbf{x}^{\#}$ is the national gross output vector. Eq. (3) indicates that in meeting the demand for any commodity c in any region $r \in R$, each region $s \in R$ will ship a share of its gross output equal to region r's share of economy-wide demand for commodity c. This relationship holds for all commodities and for demands from all regions. Our approach of including consumption expenditures on international imports (GDP plus imports) in $\mathbf{y}^f$ and including those imports in our measure of gross output ($\mathbf{x}$) is a conventional practice in type I IO multiplier analysis (e.g., Canning et al., 2016). In this study, it is necessary in order to measure domestic water withdrawals linked to the use of imports in food GDP once those imports enter the domestic market. This approach would also facilitate the measurement of international virtual water flows, although such measures are beyond the scope of this study on diet-related domestic water withdrawals.

There are clear limitations to these assumptions; however, for a national study of alternative diet outcomes, it is reasonable to assume that each U.S. region supplies a share of the national consumer demand for a commodity equal to that regions share of total production.[5] Also, for a national study of alternative diet outcomes without specific regional data on average diet outcomes, it is informative to assume that baseline national average per capita diets are representative of any regional average per capita diet. Finally, with over 340 industries represented in the direct requirement matrix used in the diet analysis, each regional industry is likely to be more represented by the national average 'production recipe' than models with more aggregated industry groups. Although biases are likely to be introduced by these three assumptions, we perceive of no a-priori reason to expect a systematic bias in national average measures of relationships between diet outcomes and associated food system water withdrawals. To relax these assumptions without supporting data that informs a more general specification is also likely to introduce biases.

2.2. Supply Chain Analysis

To further characterize water withdrawals in the U.S. food system, we conduct a supply chain analysis. Supply chains for specific food commodities are variants of the food value chain depicted in Fig. 1.

To represent this structure in the MEIO model, a matrix reduction procedure developed as an alternative to aggregation (Leontief, 1967) is employed by first reorganizing the model in Eq. (1) into supply chain industries, $S \subset C$, and non-supply chain industries, $N \subset C$ (where $S \cup N = C$), as follows:

$$\begin{bmatrix} \mathbf{x}^f[S] \\ \cdots \\ \mathbf{x}^f[N] \end{bmatrix} = \left[\begin{array}{c|c} (\mathbf{I}[S] - \mathbf{A}[S,S]) & -\mathbf{A}[S,N] \\ \hline -\mathbf{A}[N,S] & (\mathbf{I}[N] - \mathbf{A}[N,N]) \end{array}\right]^{-1} \begin{bmatrix} \mathbf{y}^f[S] \\ \cdots \\ \mathbf{0}[N] \end{bmatrix} \tag{4}$$

To reduce the dimensions of the model, we treat all non-supply chain industries as subcontractors such that each supply chain industry procures other supply chain outputs and environmental flows required by their subcontractors:

$$\mathbf{A}^S = \mathbf{A}[S,S] + \mathbf{A}[S,N] \cdot \{\mathbf{I}[N] - \mathbf{A}[N,N]\}^{-1} \cdot \mathbf{A}[N,S]$$
$$\leftrightarrow \text{ reduced dimension direct requirements} \tag{5}$$

$$\mathbf{L}^S = \{\mathbf{I}[S] - \mathbf{A}^S\}^{-1} \leftrightarrow \text{reduced dimension total requirements} \tag{6}$$

$$\mathbf{E}'^S = \mathbf{E}'[O,S] + \mathbf{L}'[S,S]^{-1} \cdot \mathbf{L}'[N,S] \cdot \mathbf{E}'[O,N]$$
$$\leftrightarrow \text{ reduced dimension environmental direct requirements} \tag{7}$$

By further partitioning the supply chain industries into stages, $S^{\sim} \subset S$ for $S^{\sim} = 1$ to 11 (see Fig. 1 for numeric concordances to stages), we estimate food-related embodied water flows by supply chain stage,

$$\mathbf{W}^{f(S\sim)} = \mathbf{E}[O, S\sim] \cdot (\mathbf{L}^S[S\sim, S] \cdot \mathbf{y}^f)'' = \mathbf{E}[O, S\sim] \cdot \mathbf{x}^f[S\sim]'', \; \forall \; S\sim \in S \tag{8}$$

$\mathbf{W}^{f(S)}$ is an $O \times S$ matrix of embodied water withdrawal measures across all supply chain stages for each water use category, and $\mathbf{W}^{f(S^{\sim})}$ is an $O \times S^{\sim}$ matrix of the same for a specific supply chain stage. Finally, embodied water withdrawals for any subset of diet expenditures, $f^{\sim} \subset f$, can be traced through the model in Eq. (8).

By way of example, consider the chemical manufacturing and financial service industry groups. More than 10 industries are classified into one of these two industry groups and at least one of these industries provides materials or services to all of the supply chain industries ($S^{\sim}$). Rather than arbitrarily allocate these among supply chain stages, the procedures summarized in Eqs. (4) to (8) treat these chemical and financial service industries as subcontractors and precisely allocate their materials, services, and water withdrawals to supply chain industries according to their actual use as measured in direct requirement and total requirement matrices.

Beyond the benefit of providing a clean and precise approach to organizing the analysis into supply chain stages, this approach also represents an alternative to aggregation of the MEIO data, since the steps in Eqs. (4) to (8) can be applied after the embodied water analysis is carried out on the full MEIO model stated in Eq. (2). The potential problems of aggregation bias in applied MEIO analysis (Lenzen, 2011; Piñero et al., 2015) are thus avoided since the matrix reduction is carried out after the analysis is applied from the disaggregated MEIO model.

[5] Import share is also factored into the trade pool model estimation of regional trade coefficients.

Table 1
Water withdrawals by USGS water use category and allocation metric to MEIO industries.
Source: DOI-USGS (2005).

USGS water use category	USGS 2005 water use estimate (Mgal/day)	USGS 2005 water use estimate (%)	Allocation metric	Allocation data source
Aquaculture	8780	3%	N/A; assigned to one industry	
Domestic	3830	1%	N/A; assigned to final demand vector	
Industrial	17,000	5%	Employment data by county	County Business Patterns (2007)
Irrigation	128,000	37%	Acres irrigated by county by crop; water applied by state by crop	Census of Agriculture (2007); Farm and Ranch Irrigation Survey (2008)
Livestock	2140	1%	Inventory by animal by county; water consumed by animal	Census of Agriculture (2007); Lovelace (2009)
Mining	2310	1%	Employment data by county	County Business Patterns (2007)
Public supply[a]	44,200	13%	MEIO coefficients	MEIO matrix based on data from the Bureau of Economic Analysis (2007)
Thermoelectric	143,000	41%	N/A, assigned to one industry	
Total	349,000	100%		

All freshwater estimates. Since this table summarizes source data, we leave the units in Mgal/day. The conversion rate is 1 liquid gallon = 3.78541 l.
For the industries defined by USGS as commercial, the self-supplied water use was assumed to be zero since there is no estimate from USGS in 2005.
[a] Net public supply is allocated, rather than total public supply, to the MEIO industries. Net public supply = (public supply − domestic deliveries).

2.3. Data Development for the Multiregional Environmental Input-Output Model

Our research focuses on blue water because it is considered the scarcest (Hoekstra et al., 2011). The U.S. Geological Survey (USGS) has collected data on water withdrawals in the United States since 1950 and reports the estimates in five year increments. These data represent direct water use. To assess water use in the U.S. food system and estimate indirect water use, we allocate the 2005 USGS water data in broad, water use categories to the more detailed economic industries in the MEIO (DOI-USGS, 2005). The MEIO matrix, developed by USDA's Economic Research Service (Canning et al., 2017), includes 344 economic industries and is based on the Bureau of Economic Analysis's (BEA) most recent benchmark industry accounts from 2007 (DOC-BEA, 2007). We allocate the 2005 USGS water data because they correspond most closely with BEA data on industry accounts.

As a first step in allocation, a concordance is created to assign each USGS water use category to one or more industry users in the U.S. economy. We begin with the 1987 Standard Industrial Classification (SIC) codes associated with each water use category presented in Table 3 of Kenny (2004). Production in the MEIO model is categorized into North American Industry Classification System (NAICS) industry groups. We map the industries by NAICS to water use categories via SIC.

Next, additional data sources are necessary to allocate the water use data since a large portion of water is self-supplied and the purchased water coefficients derived from the MEIO do not apply. We use a variety of metrics in allocation which are summarized in Table 1. We allow for geographical heterogeneity of water resources and use, by using county-level data on irrigated acreage by crop from the 2007 Census of Agriculture coupled with state-level data on water application rates by crop from the 2008 Farm and Ranch Irrigation Survey to allocate the irrigation water use (USDA-NASS, 2007, 2008). Some of the data from the Census of Agriculture are suppressed, so we estimate the suppressions using a constrained maximum likelihood estimator model which relies on hierarchical relationships within the data as constraints (Canning, 2013). Similarly, we allocate the livestock water use category using estimated county-level livestock inventory data from the 2007 Census of Agriculture. These data are coupled with daily water intake rates by animal (Lovelace, 2009). The allocation metric for industrial and mining water use categories is county-level employment data from the 2007 County Business Patterns (DOC-Census, 2007).

For the water that is publically-supplied, we use the purchased water coefficients by industry from the MEIO matrix to allocate water withdrawals from the USGS categories to the specific economic industries. USGS did not estimate self-supplied water use for commercial industries, so it is assumed to be zero.

2.4. Linking Water and Cost to Food Items

We link the foods and beverages consumed in the United States to commodity groups that are based on food expenditure categories from the MEIO data. We use consumption data from the dietary intake portion of the 2007–2008 National Health and Nutrition Examination Survey (NHANES), called What We Eat in America (CDC, 2013). NHANES is a nationally-representative survey designed to assess the health and nutritional status of Americans and is released in two year cycles. The dietary data are collected through an interview where respondents recall what they ate in the past 24 h. Because of the dietary recall nature and the complex survey design of NHANES, these data capture the diversity of American diets which vary based on age, gender, and region, among other factors. The 2007–2008 cycle of the survey corresponds with the most recent detailed IO data from 2007.

To link these as-consumed items to the commodity groups, we use the Food and Nutrient Database for Dietary Studies (FNDDS 4.1) which breaks the food items into ingredients[6] (USDA-ARS-FSRG, 2010a). With the grams of food as consumed organized by commodity group, we are able to compute 38 water pathways with unique gallons per gram ratios. These 38 pathways are obtained from combinations of the 74 food commodity groups in the MEIO. The aggregations were made to eliminate some ambiguities about correct mappings of NHANES food items to the MEIO commodity groups. We map these ratios back to each food item using a weighted average of each food item's commodity makeup. Specifically, each food is a weighted average composite of the 74 food and beverage expenditure commodities, where the weights are based on the share of total grams consumed that is mapped to each expenditure commodity. With a price per gram estimated at the expenditure commodity level computed as annual expenditures over annual grams consumed, this calculation captures the actual costs (including loss and waste) of consumption. For example, if a household purchases a bunch of bananas but only consumes half of them, then the price of eating one banana is purchasing two bananas. The resulting linked NHANES/MEIO dataset allow us to measure the embodied water withdrawals to produce and market the foods and beverages reported in NHANES.

[6] Specifically, the SR-links file from the FNDDS 4.1.

2.5. Diet Scenario Analysis

We explore four different diet scenarios that are combinations of two different objective functions and two USDA Food Patterns adaptations from the 2010 DGA. The USDA Food Patterns recommend consumption by food group at 12 caloric levels and serve as an example of how to follow the DGA with an omnivore or lacto-ovo vegetarian diet (USDA and HHS, 2010). The lacto-ovo vegetarian adaptation of the USDA Food Patterns is a type of vegetarianism that allows eggs and dairy products, but no meat, poultry, fish, or seafood. In the lacto-ovo vegetarian adaption, meat, poultry, and seafood under the protein foods group are replaced by beans, peas, and soy products while eggs, nuts, and seeds remain as important sources of protein (Appendix 8 in USDA and HHS, 2010).

First, we model a minimal change to a healthy diet from current consumption, represented by the NHANES dietary intake data, or what we refer to as the Baseline Diet. In other words, we are creating hypothetical healthy diets that align with the DGA which are as close as possible to how Americans are currently eating (Canning et al., 2017). Secondly, we model healthy diets that minimize blue water withdrawals throughout the U.S. food system. This model explores the lower bound of water withdrawals while still providing Americans with a healthy, nutritionally-adequate diet.

The Food Patterns make up the model constraints (USDA-ARS, 2014), along with nutrient constraints (Appendix 5 in USDA and HHS, 2010), calorie constraints (Appendix 6 in USDA and HHS, 2010), and a cost constraint that maintains or reduces the wholesale cost of the Baseline Diet. The cost per food item is derived from the conventional IO model in dollars while the blue water withdrawals in gallons per gram of each food item in the Baseline Diet (model input data) uses the MEIO data described in Section 2.4. The model's constraints are weighted based on the age and gender demographics of the NHANES participants.

We abbreviate our four diet scenarios as MDO (minimum difference omnivore), MWO (minimum water omnivore), MDL (minimum difference lacto-ovo vegetarian), and MWL (minimum water lacto-ovo vegetarian) for reporting purposes.

To carry out the diet analysis, we must translate what Americans are buying into what they are eating. We link the 74 final demand food and beverage categories, which are linear combinations among the C commodities of the $\mathbf{y}^f$ vector introduced above, to the grams of foods and beverage items consumed through the matrix $\mathbf{Q}$ of dimension $C \times G$, where G = food items = {1, …,4067}. Another way to describe the matrix $\mathbf{Q}$ is that it is the set of all food and beverage items as consumed, organized into the commodity groups as purchased. The number of columns equals the number of food and beverage products as consumed by Americans ages 2 and above, and the number of rows equals the number of consumer food and beverage commodity groups as purchased. For example, whole milk maps 100% to the fresh milk commodity, so it is a vector of all zeroes except for the cell that intercepts the fresh milk commodity row. An example of a multi-ingredient food would be shrimp stir fry. In this case, 23% of the grams consumed maps to the shellfish commodity, 3% of the grams map to the oil commodity, and 75% of the grams map to the vegetables commodity based on the proportions of these ingredients used in the meal.[7] For the diet analysis, we are only concerned with food items consumed, so we can collapse the rows in the $\mathbf{Q}$ matrix: $\mathbf{q}^0 = \{\mathbf{q}^0_g\} = (\mathbf{i}' \times \mathbf{Q})'$. The baseline diet is summarized in the column vector, $\mathbf{q}^0$, as the average daily grams consumed across G food items. In the ensuing analysis, both diets and constraints are analyzed across 16 cohort groups, defined over 8 age ranges for both genders corresponding with the American Community Survey, a public data source allowing for estimation of age-gender population counts at the county level. To conserve on notation, additional cohort notation is omitted and the reader should keep in mind that all diet-related vectors and matrices are separately developed for each of the 16 cohorts, and cohort specific optimization models are independently solved. All results will be reported as the average across all 16 cohorts, weighted by cohort population counts.

Let $\mathbf{N}$ (Greek capital letter Nu) represent a $N \times G$ matrix populated with conversion factors that transform grams as consumed for each food and beverage product into units corresponding to all specific dietary requirements in the DGA, N = {1, …,49}. A list of all 49 food attributes is provided in appendix table C.2 in Canning et al. (2017). For example, the $\mathbf{N}$ matrix will transform grams of a fresh apple reported in the $\mathbf{q}^0$ vector into calories,[8] cup equivalents of fruits, and many other nutrition metrics. Next, let $\mathbf{n}^+$ and $\mathbf{n}^-$ represent the goal and limit vectors, reporting the dietary goals and dietary limits across all metrics including calories, Food Patterns components, and nutrients. These are the complete 2010 DGA metrics, subsets of which only specify (i) goals (lower bound), (ii) limits (upper bound), or (iii) both goals and limits. Then for any diet outcome $\mathbf{q}^1$ to be in alignment with the DGA, the following two conditions must hold: $(\mathbf{N} \times \mathbf{q}^1) \geq \mathbf{n}^+$ and $(\mathbf{N} \times \mathbf{q}^1) \leq \mathbf{n}^-$. These two inequality expressions state that (for each cohort) the average observed diet represented in $\mathbf{q}^1$ has the embodied dietary characteristics, as measured by $\mathbf{N} \times \mathbf{q}^1$, that at least meets all consumption goals ($\mathbf{n}^+$), but does not exceed all consumption limits ($\mathbf{n}^-$).

To get daily water withdrawals of food consumed for each expenditure group, in liters per gram, we rely on the grams consumed by expenditure group, represented by $\mathbf{q}^0_c = \mathbf{Q} \times \mathbf{i}$, and divide this vector[9] into $\mathbf{w}^f = \mathbf{i}' \times \mathbf{W}^f$ (Eq. (8)). We map this total daily water withdrawal per gram vector out to each food item using $\mathbf{Q} \times ((\mathbf{i}' \times \mathbf{Q})'')^{-1}$. This results in $\boldsymbol{\omega}^f$, a G element vector summarizing average water withdrawals from all sources per gram consumed. In the same way, a dollars per gram vector is derived by using $\mathbf{y}^f$ in place $\mathbf{w}^f$, producing $\mathbf{p}^f$, a G element vector summarizing average prices per gram consumed.

For our model-derived minimum difference healthy diets, we seek a diet that is as close as possible to the baseline diet while also meeting either the DGA omnivore or lacto-ovo constraints and does not exceed baseline costs. The basic model is stated as:

$$\text{Min } Z1 = (\mathbf{q}^1 - \mathbf{q}^0)' \times \{(\mathbf{q}^0)''\}^{-1} \times (\mathbf{q}^1 - \mathbf{q}^0) \tag{9}$$

subject to

$$\begin{aligned}
&\text{a) } \mathbf{N} \times \mathbf{q}^1 \geq \mathbf{n}^+ \text{(DGA goal constraints—omnivore or lacto−ovo)},\\
&\text{b) } \mathbf{N} \times \mathbf{q}^1 \leq \mathbf{n}^- \text{(DGA limit constraints—omnivore or lacto−ovo)},\\
&\text{c) } \mathbf{q}^0, \mathbf{q}^1 \geq 0 \text{(non−negative consumption constraint)},\\
&\text{d) } (\mathbf{p}^f)' \times \mathbf{q}^1 \leq (\mathbf{p}^f)' \times \mathbf{q}^0 \text{ (budget limit constraint)}
\end{aligned} \tag{10}$$

We are seeking to minimize $Z1$, which measures the sum of squared percentage difference between healthy and baseline diets. The complete constraint sets are stated in Eq. (10)a to d.[10]

A second model seeks a diet that minimizes total embodied water withdrawal while also meeting either the DGA omnivore or lacto-ovo constraints, and does not exceed baseline costs. The basic model is stated as:

$$\text{Min } Z2 = (\boldsymbol{\omega}^f)' \times \mathbf{q}^2, \tag{11}$$

subject to constraints Eq. (10)a to d where $\mathbf{q}^2$ is a the endogenously-determined MWO or MWL diet.

The four healthy diet scenarios identified in Table 2 are solved for each cohort group. We implemented our model in GAMS 24.7.4 and used CONOPT3 3.17A as the NLP solver. All optimization studies solved

[7] These percentages are rounded.

[8] In our work, 1 cal refers to a kilocalorie, or food calorie, equivalent to 4184 J.

[9] Average daily consumption for each cohort is multiplied by the cohort population.

[10] Canning et al. (2017, Appendix C) discusses the maximum likelihood properties of a model like our MDO scenario, including conditions in which a solution is the most statistically representative of current (2007/08) American diets already meeting the DGA.

Table 2
Creating four diet scenarios.

		USDA Food Patterns Adaptation	
		Omnivore	Lacto-ovo vegetarian
Model Objective Function	Minimum difference	MDO	MDL
	Minimum water	MWO	MWL

in minutes and were carried out on a desktop computer, each case running on an × 64 based 2.8 GHz processor with a memory allocation of 16 gigabytes.

3. Results

We find that the U.S. food system uses 369 billion liters of water per day,[11] or 28% of the blue water withdrawn in the United States. The daily water withdrawals throughout the U.S. food system is equivalent to 148,000 Olympic-sized swimming pools. Over a year, these water withdrawals would approximately fill Lake Tahoe, the sixth largest lake by volume in the United States after the Great Lakes.

Blue water withdrawals can be broken out into surface and groundwater sources, as defined by USGS. For all uses of blue water, 77% is surface water while 23% is ground water. For U.S. food system blue water use, the proportion of surface water decreases, but still makes up the largest share at 71%. Groundwater contributes 29% of water withdrawn in the U.S. food system.

When reporting our results, we make the distinction between total food system water use and diet-related water use. Total food system water use measures all supply chain stages including all household water use. Water used by households is the second most of all food system stages at 75 billion liters/day. Total household water use measures both diet-related household water use (i.e., drinking water and water added as an ingredient) that we can allocate to specific food items and non-diet-related household water which we cannot. We cannot say by how much water use in the kitchen would change or how many more (or less) grocery store trips one may make due to different food items consumed. This category also includes the water embodied in food-related energy used by households such as the gasoline needed for trips to the grocery store or the electricity to run kitchen appliances. Examples of non-diet-related household water includes water used to wash vegetables, wash dishes, and boil water for cooking.

The diet-related water, the subset of the total water use in the U.S. food system, is endogenous in the diet model. The diet-related water results are presented below.

To assign the 4000+ reported food and beverage items to a broader food group for reporting purposes, we rely on the USDA food classification system in which multi-ingredient foods are grouped into categories by a representative ingredient in that food (see Appendix B in USDA-ARS-FSRG, 2010b). For example, an omelet made up of ingredients such as eggs, ham, milk, margarine, and salt, is coded beginning with a 3, so is in the Eggs and Egg Product category for diet reporting purposes.

3.1. Baseline Diet Results

Our results indicate that 295 billion liters/day, or 22% of blue water withdrawals, are attributed to diet-related water use, or all of the foods and beverages purchased by or for the domestic population of the United States. The U.S. diet makes up only 54% of agricultural production receipts; the remaining 46% includes production of fiber crops, crops grown for biofuel production, and exports (author calculations based on DOC-BEA, 2007). Therefore, the 22% of embodied water that is diet-related does not represent all agricultural water use; agriculture's proportion would be higher.

Table 3 presents results on diet-related water use in the U.S. food system by stage. Water withdrawals for crop production is the highest at 217 billion liters/day. Energy services also uses a substantial amount of water. This category represents energy used throughout all of the stages of the food system, except for household energy use. It includes the water embodied in diesel for tractors at the production stage and electricity for the grocery store at the distribution and marketing stage. The amount of water withdrawn to produce energy used in the U.S. food system indicates the nexus between these two resources.

Agricultural production of crops is an important and primary user of water, making up 74% of diet-related water use, or 59% of total food system water use in the United States. This means that the food system stages further downstream contribute over two-fifths of total water use, not a negligible amount.

The meat, poultry, fish, and mixtures food group uses the most diet-related water across all supply chain stages with 69 billion liters/day. The grain products follow with 62 billion liters/day and sugar, sweets, and beverages come in third with 57 billion liters/day. This does not necessarily mean that these three product categories are water inefficient, but they use the bulk of water based on current American consumption; it is well-documented that Americans are overconsuming meat, refined grains, and added sugars (Canning et al., 2017; USDA and HHS, 2015). We can also look at these food groups and the water use by stage in the U.S. food system. At the crop production stage, grain products use the most water with 48 billion liters/day. Sugar, sweets, and beverages use the most water in the processing and packaging stage and energy services at 2 billion liters/day and 13 billion liters/day, respectively. The meat, poultry, fish, and mixtures category uses the most water in both the livestock production stage and distribution and marketing stage.

Focusing on the meat, poultry, fish, and mixtures category, 17 billion liters/day is required at the livestock production stage for the animals' drinking and servicing water. Even more water, 38 billion liters/day, is embodied in the final meat product purchased due to the amount of water used in the agricultural production of livestock feed. Table 3 shows freshwater withdrawals by stage for all food groups.

3.2. Healthy Diet Scenario Results

We present four healthy diet scenarios, all conforming to the calorie, nutrient, and Food Patterns recommendations in the DGA. Additionally, we include a cost constraint in the modeling to maintain the food budget of the Baseline Diet. The MDO and MDL diets result from the minimum difference model which represents the shortest route to eating healthy. Therefore, many of the same food items that are in the Baseline Diet are also in these healthy diet scenarios. However, there are notable shifts in both the types and quantities of food items that comprise these diets. For example, calories from fruits and vegetables increase in these scenarios given the known and documented underconsumption of these food groups in the Baseline Diet (Canning et al., 2017; USDA and HHS, 2010). Calories from food items in the milk and milk products and the legumes, nuts, and seeds categories increase while calories from the sugars, sweets, and beverages categories decrease. The meat, poultry, fish, and mixtures calories decrease in the MDO diet while this category is eliminated in the MDL diet, by definition. These results are shown in Fig. 2.

We find that a healthy diet that changes minimally from the Baseline Diet and is aligned with the DGA, requires 1181 daily liters per

[11] Source data were originally in million gallons per day. "Units of millions or billions of gallons per day do not represent actual daily rates, but rather are used to express total amounts as an average daily rate for 1 year. For example, irrigation water may be applied only during parts of the year and at variable rates; therefore, the actual rate of application at any given time during the growing season is different from the average daily rate based on 365 days in a year." (p. 2 in Kenny et al., 2009).

Table 3
Blue water withdrawals by supply chain stage and food group for the Baseline Diet.
Source: Authors' calculations.

Food group	Milk and milk products	Meat, poultry, fish, and mixtures	Eggs and egg products	Legumes, nuts, and seeds	Grain products	Fruits	Vegetables	Fats, oils, and salad dressings	Sugars, sweets, and beverages	Total
	Million liters per day, U.S. population									
Crop production	13,114	37,528	3463	7081	48,440	30,184	34,205	2642	40,265	216,921
Livestock production	1518	16,958	425	219	2608	296	456	32	462	22,975
Processing & packaging	423	1688	52	142	1380	317	373	36	2037	6449
Distribution & marketing	403	1189	35	66	611	138	177	37	1073	3728
Energy services	4202	12,072	481	870	8734	2215	2583	363	12,766	44,286
Household_diet-related	1	1	0	1	9	1	1	0	180	194
Total diet-related water use	**19,661**	**69,437**	**4457**	**8378**	**61,781**	**33,150**	**37,795**	**3110**	**56,783**	**294,552**
Household_non-diet-related	–	–	–	–	–	–	–	–	–	74,771
Total food system water use	**–**	**–**	**–**	**–**	**–**	**–**	**–**	**–**	**–**	**369,324**

Food groups are defined by grouping food and beverage items by first digit of USDA food code. Household_diet-related is the direct water use from the kitchen faucet used for drinking or as an ingredient to food items. Household_non-diet-related is the remaining direct and indirect water use by households that is not allocated to individual food items since we cannot determine how household water use (e.g., running the dishwater, rinsing vegetables) would change in response to dietary changes. Numbers may not sum to total because of independent rounding.

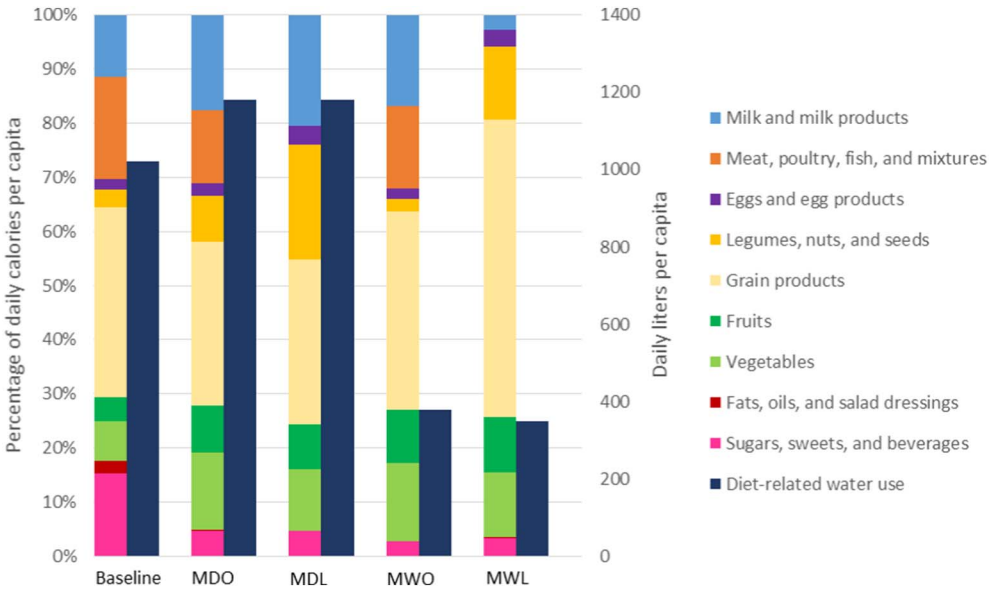

Fig. 2. Comparison of calories and diet-related water use for the Baseline Diet and healthy diet scenarios.
Note. The stacked bars correspond with the left vertical axis and the diet-related water use bars correspond with the right vertical axis. 100% = average daily calories in each diet scenario. All of these caloric totals fall between the weighted average amount of calories recommended by the *Dietary Guidelines for Americans, 2010* (USDA and HHS, 2010) ± 5% allowed in the model. The range is between 2070 (Baseline) and 2213 (MDL) calories per capita per day.
Source: Authors' calculations.

capita, or 16% more water than the Baseline Diet. Interestingly, the 16% increase is for a shift to either the healthy omnivore (MDO) or lacto-ovo vegetarian (MDL) diet. The cost constraint is binding in the MDO diet meaning it has the same daily per capita wholesale cost as the Baseline Diet while the MDL diet's cost decreases slightly, by 4 cents.

In the diet model that seeks to find the lower bound of water embodied in diets with the minimum water objective function, our results show that water reductions are possible through dietary change. In the MWO diet, water is substantially reduced to 379 daily liters per capita, or 63% less than the Baseline Diet's embodied water use. Greater reductions to 348 l per capita per day (66%) result from the MWL diet which excludes the meat, poultry, and fish. To put the decreases in embodied water in context, if the entire American population shifted such that either of these minimum water diets became the average American diet, blue water withdrawals filling approximately 74,000 to 78,000 Olympic-sized swimming pools could be saved each day.

Similar calorie changes take place in the MWO and MWL diets as in the MDO and MDL diets. Even though the MWO and MWL must meet the Food Patterns constraints from the DGA which impose diet diversity, they are able to do so with approximately 1% of the number of food items from the Baseline Diet. This indicates that the minimum water diets are an extreme departure from current American diets. The MWO and MWL diets are less costly, at $2.03 and $1.78 per capita per day. Since these wholesale costs are less than half of that of the Baseline Diet, these results signal that there may be a positive relationship between embodied water and dietary cost.

4. Discussion & Conclusions

Our research indicates that while healthier U.S. diet outcomes and blue water conservation can be synergistic, there is also potential for these goals to be competing. This result heightens the importance of studying the interactions of diet outcomes and blue water use throughout the food system.

This research quantifies current direct and indirect blue water use by detailed economic sectors, and specifically, those related to food, in

the United States. Water for food in the United States has not been looked at extensively in the current literature. Our systems perspective to measure water throughout the stages of the U.S. food system extends the scope of water use beyond irrigation at the farm level. We also link water to food items that Americans are consuming which provides the framework for research simulating the tradeoffs between dietary changes on water use in the U.S. food system. This can be informative for policy discussion surrounding food system sustainability and the transition to healthier diets. This framework can also be informative in studies of policy options related to sustainable food security on a global scale. Many nations maintain a system of national accounts that can be adapted to the framework presented in this study.

We find that the U.S. food system uses a total of 369 billion liters of blue water per day and the majority of water embodied in the U.S. diet is for irrigating crops. We also see that energy services and households are substantial water users along the food supply chain. When looking at specific food groups, we find that a large proportion of crop irrigation is embodied in animal products through feed, as illustrated by the meat, poultry, fish, and mixtures category.

When considering four healthy diet scenarios that conform to the DGA, diet-related water requirements both increase and decrease, depending on the scenario. In the MDO and MDL diets, water use increases by 16% whereas water use decreases by 63 and 66% in the MWO and MWL diets, respectively. The change in water requirements are driven by the amount and types of food items chosen by the diet optimization model.

Our results are consistent with the two papers that consider American diets and the 2010 DGA that also show a healthy diet increases blue water use (Birney et al., 2017; Tom et al., 2016). In Tom et al. (2016), the healthy diet scenario that meets the recommended food mix and calories in the DGA (Scenario 3), blue water increases by 10%. Birney et al. (2017) find that following the DGA, while keeping food waste and loss rates constant, blue water would increase by 15%.

Comparing our estimates to the literature, Tom et al. (2016) estimate the annual blue water footprint and report the average to be about 40 billion cubic meters. Converting our estimates of diet-related water use to the same units equals almost 108 billion cubic meters. Birney et al. (2017) estimate a total of 162,000 l of blue water is required for the current average American diet annually where our estimates are along the lines of 373,000 l for diet-related water use. There is variation in time period, geography, diet definition, methodology, and data, all contributing to differences in the results. In each comparison, our results for the water required to produce the current diet are much higher. However, both Birney et al. (2017) and Tom et al. (2016) rely on water footprints (Hoekstra et al., 2011) which decouples the consumptive and non-consumptive water use (return flow), where we use water withdrawals (USGS, 2005). This is likely the primary reason our estimates are greater. Even with these differences, our results in percentage change are comparable.

Our estimates differ in magnitude with the estimates in Vanham et al. (2013b) as well. For example, the authors report 299 l of blue water per capita per day in their reference diet and we find 1022 daily liters of diet-related water in our Baseline Diet, or 1279 l of total food system water use. However, not only differing in method, data, and diet definitions, this paper is also considering four EU geographical zones, rather than the United States.

Using similar diet modeling, Donati et al. (2016) find that the largest reduction in blue water results from a model which integrates environmental and economic objectives; that is, reduced environmental impact and dietary cost can be synergistic. This is consistent with our results that use the minimum water objective function and produce healthy diets that are lower-cost. Also using model-generated diets, but analysing GHGE as an environmental impact, Macdiarmid et al. (2012) find that healthy diets can reduce GHGE and lower the cost of diets without eliminating meat or dairy. Due to our model design, all of our diets include meat or dairy products since consumption is required by the Food Patterns constraints from the DGA.

Our conclusions differ in some ways from the literature which has been conclusive that a healthy or plant-based diet requires less water resources (e.g., Marlow et al., 2009; Vanham et al., 2013a; Vanham et al., 2013b; Vanham et al., 2016). We find that when making minimal changes from the Baseline Diet to either an omnivore or lacto-ovo vegetarian diet, water use increases by 16%. In this case, the MDL diet our model produced is no more water efficient than MDO, a diet including meat, poultry, fish, and seafood items. However, when considering the minimum water objective function and resulting MWO and MWL diets, there is a 3% greater reduction in water for the laco-ovo vegetarian diet.

This research indicates that that although comparing individual food items can be illustrative (animal-based versus plant-based products), comparing a whole diet provides a more complete analysis of the differences between an omnivore and vegetarian eating pattern. For example, it is easy to imagine that a bowl of spaghetti and marinara sauce requires less water than the same bowl of spaghetti with ground meat added to the marinara sauce. However, when considering the basket of foods that Americans would need to eat to meet the daily dietary requirements and maintain or reduce the household food budget, the differences in water requirements are muted between the omnivore and vegetarian diets.

Our results demonstrate that sustainable nutrition is a complex research area especially when considering three important attributes of food items: health impact, environmental impact, and cost.

4.1. Limitations and Future Directions

Although the evidence of food-related water use for alternative diets in the United States is limited, the potential for diet/water tradeoffs is evident in these studies (Birney et al., 2017; Tom et al., 2016). Studies on other countries have produced evidence of synergies between healthy diets and reduced water use (Vanham et al., 2013a; Vanham et al., 2013b; Vanham et al., 2016). With food systems worldwide becoming increasingly global, this contrast of findings from studies in other countries illuminates a need to extend empirical studies to a global perspective and to bring in the consideration of virtual water flows, the water embodied in traded goods.

Another future direction of this research could be expanding the scope of environmental impacts and including other metrics beyond blue water use as other U.S. studies do (Birney et al., 2017; Eshel et al., 2014; Gephart et al., 2016; Marlow et al., 2009; Tom et al., 2016). Examples of additional impacts considered include GHGE and the use of land, fertilizer, energy, and nitrogen. Using the same MEIO framework as we do in this paper, other research has explored the fossil fuels embodied in American diets (Canning et al., 2017).

Our analysis assumes that these diets are produced with 2007 food-system technologies since this is the most recent year of detailed data available. Additionally, implicit in the IO models is the assumption of perfectly elastic primary factor supply curves. This means that we assume the U.S. food system could supply any amount of the food items that are part of the healthy diets without affecting prices and that extends to import products, too. A limitation of these assumptions if major shifts in American diets take place is that supply constraints may occur for certain foods, leading to price changes that affect affordability, purchasing choices, and the role of imports in the food system. It also ignores the possibility that water use intensity may change with changing cropping patterns and with other production adjustments.

This research could be expanded to address these limitations. For example, incorporating producer feedback, such as allowing for factor substitution and factor supply constraints can capture the relative factor price and food cost changes. Including a demand system which models consumer response to price changes will account for the role of consumer feedback. More detailed land use research could inform how producers are able to respond to changes in demand and adapt to

resource constraints. For example, how and where will land for specialty crops be brought into production? The data for this analysis was built up from state and county level sources, and the IO framework can be adapted to incorporate producer and consumer feedback.

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